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A 2.5-MEGAWATT GRAPHITE HEATER FOR NITROGEN GAS

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NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 68-109

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A 2.5-MEGAWATT GRAPHITE HEATER FOR NITROGEN GAS

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ABSTRACT: This report describes a low-voltage, single-phase graphite heater which will deliver 1.5 pounds of nitrogen gas per second at a pressure of 600 atmospheres and at temperatures up to 2500° Rankine.

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WHITE OAK, MARYLAND

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A 2.5-MEGAWATT GRAPHITE HEATER FOR NITROGEN GAS

This report describes the physical arrangement and presents test results from a graphite resistance heater used to heat nitrogen gas to a temperature of 2500° Rankine at pressures up to 600 atmospheres.

The purpose of this heater is to heat high-pressure gas, for a Mach 12 wind tunnel, to a temperature sufficient to prevent equilibrium condensation in the test section.

The authors would like to acknowledge the contributions of Messrs. J. Holt and W. Brewbaker to the success of this project.

E. F. SCHREITER
Captain, USN
Commander

L. H. Schindel
L. H. SCHINDEL
By direction

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ILLUSTRATIONS

A 2.5-MEGAWATT GRAPHITE HEATER FOR NITROGEN GAS

1. INTRODUCTION

As part of a program to add Mach 12 and 17 wind tunnel capabilities to the existing aerodynamic facilities at the Naval Ordnance Laboratory (NOL), a gas heater development effort was initiated. The range of gas supply requirements, using nitrogen as the working fluid, for the proposed aerodynamics facility are shown in Figure 1. As shown in the figure, maximum supply gas requirements at Mach 12 are eight pounds per second at a pressure of 700 atmospheres (10,300 psi) and a temperature of 2500° Rankine. At Mach 17 the maximum required flow rate is 1.5 pounds per second at 700 atmospheres and 3900° Rankine.

The temperatures specified are necessary to prevent equilibrium condensation during expansion of the gas in the nozzle. Data from references (1) and (2) were used to determine liquefaction conditions and supply temperature requirements.

The design of the gas heater was based on test experiences reported in references (3) and (4) where temperatures achieved were in the required range but pressure and power requirements were much lower, i.e., 100 atmospheres at 0.1 megawatt. To avoid excessively large elements and consequently low electrical resistance, it was necessary to utilize three elements for the Mach 12 conditions. The three elements would be arranged electrically in a three-phase wye configuration, thus each element would carry one-third of the required gas flow.

To experimentally develop, evaluate and optimize heater configurations, the following test programs were initiated:

1. Develop a single element to satisfy one-third of the Mach 12 requirement. Figure 2 shows the operating requirements for this heater.

2. Develop an element to satisfy the full-scale Mach 17 requirements.

These test programs were chosen because the same test setup could be used for both tests by simply changing nozzle throat size and element passage configuration.

This paper presents results of the Mach 10 phase of the test program.

2. PRIMARY TEST EQUIPMENT

A line diagram of the flow circuit is shown in Figure 3. Major components of the system are:

1. Nitrogen Supply System

The nitrogen supply system consists of a 1200-gallon liquid nitrogen storage tank, a 15,000-psi piston-type liquid nitrogen pump having a 0.3-pound per second pumping rate, a vaporizer unit, a 700-cubic foot, 15,000 psi gas storage reservoir which consists of the breach ends of 19, 16-inch Naval gun liners, a one-inch inside diameter delivery pipe, cut-off and control valves, and a venturi-type flow meter with adjustable plug throat.

2. Electric Power Supply

Electric power is supplied to the graphite heater by a 8.25-million volt-ampere, three-phase combined induction regulator and step down transformer unit designed for an intermittent duty cycle of four minutes "ON" and two hours "OFF" when operated at maximum rated load. The output voltage is smoothly variable from 10 to 100 percent at any one of eight transformer tap settings. The tap settings are in 440 volt increments with a maximum setting of 3520 volts. With the transformer load being essentially resistive (unity power factor), the maximum current at a given tap setting is that required to attain 8.25 megawatts when operating at maximum voltage for the tap setting. Further, the power supply is designed to deliver a maximum power of 2.75 megawatts to a single-phase resistive load with a maximum allowable current of 10,800 amperes at a transformer tap setting of 440 volts. Figure 4 shows the rated operating time of the power supply as a function of output current at a 440-volt tap setting.

Power is delivered to the heater by a system of exposed flat copper bar busses. Each conductor consists of four 4 x $\frac{1}{4}$ inch bars separated from each other by $\frac{1}{4}$ inch air spaces.

All gas supply components and the power supply for the heater development tests are installed in such a manner that they can be used in the wind tunnel circuit without modification or relocation.

3. HEATER ASSEMBLY

Figure 5 shows a cross-sectional view of the heater assembly and Figure 6 is a photograph of the test assembly.

The electrical circuit consists of a water-cooled copper electrode which passes through the pressure vessel end closure with suitable pressure seals and electrical insulation provided. From the electrode a flexible connection (three 4/0 AWG non-insulated welding cables) is made to the graphite element. This connection permits freedom for thermal growth of the element relative to its supports. A nylon liner is placed inside the vessel at the flexible cable location to prevent a short circuit to the vessel wall. The graphite heating element is then threaded into the nozzle inlet block, thus providing a ground connection and at the same time preventing gas from by-passing the element.

Surrounding the heater element is a pyrolytic graphite sleeve housed in a stainless steel tube which is attached to the nozzle inlet section and guided at the other end with freedom to expand. This assembly serves as a heat barrier to protect the pressure vessel and also as a support for the heating element. The element is supported in the tube at the gas inlet end (cold end) and at a center station with freedom for expansion at each location. The center guide is electrically insulated from the housing by boron nitride, while the cold end guide is insulated by a high-temperature fiber material called Tayloron manufactured by Taylor Fiber Company, Norristown, Pennsylvania.

The heating element and associated components are housed in a pressure vessel rated for 15,000 psi service.

4. HEATER ELEMENT

The heater element, shown in Figure 7, is fabricated from graphite supplied by Ultra Carbon Corporation, Bay City, Michigan, with the designation YU-60ST. This material is a high purity, small grain size graphite which has an electrical resistivity of approximately 0.0009 ohm-in at room temperature. Elements reported in reference (3) and some of the first elements used in this program were made of graphite type ZTA supplied by the Union Carbide Corporation, New York City. Resistivity of this material is almost identical to the YU-60ST. Elements made from the YU-60ST offered two distinct advantages for this application; namely, a fabricated element assembly costing approximately 10 percent that of ZTA and there is no material length restriction. The ZTA graphite material is supplied in maximum lengths of 12 inches.

The element assembly, Figure 7, consists of one tube with a helical passage machined on the outside surface and surrounded by a second tube. This arrangement provides a single spiral gas flow passage. The element sleeves are fabricated in three equal length sections which are threaded together. This arrangement serves two purposes; namely, it simplifies element machining operations and permits replacement of only damaged parts rather than complete elements. The element tubes are made as thin walled as is structurally acceptable in order to provide high resistance, thus avoiding extremely high current at a given power requirement. This is why the material resistivity, mentioned previously, is extremely important. The element is provided with threaded ends for attachment to the nozzle end and to accept the electrical connector at the cold end.

5. INSTRUMENTATION

Figure 8 is a schematic layout of the test instrumentation arrangement. All pressures were measured using 0 to 10,000 psi strain-gage type transducers with their outputs fed directly into two-channel strip chart recorders. Supply gas temperature was measured with an iron-constantan thermocouple while exhaust gas temperature was measured by two independent platinum versus platinum--10 percent rhodium thermocouples. The temperatures were also recorded on strip chart recorders. Current and voltage were measured using current and potential transformers and recorded on a two-channel strip chart recorder. Continuous recording of these parameters permitted immediate detection of failure in any part of the system during a heater test. For example, a vessel closure pressure seal failure during a test would appear as an increased pressure drop across the flow meter but affected no other data. An element break (one sleeve only) would show an abrupt decrease in pressure drop across the heater and a drop in temperature with slight increase in pressure drop across the flow meter, but in many cases no detectable change in current or voltage. One major improvement that could be made to the instrumentation setup would be to use a differential pressure gage at the flow meter to increase accuracy of pressure drop data. This, in turn, would provide an accurate determination of mass flow. In a leak tight system an accurate measurement of mass flow can be used to determine gas temperature. This is important when the magnitude of the temperature prohibits use of standard thermocouples.

6. DISCUSSION OF TEST RESULTS

The heater assembly and element configuration shown in Figures 5 and 7 were arrived at after a number of modifications during the test program. The major problem areas encountered during the development were at the element connection to the nozzle inlet block (ground), the joints in the element itself and at the copper-to-graphite electrical connection on the cold end. In all cases, except at the cold end, electrical connection failures resulted from combined thermal and pressure stresses and were corrected by minor design changes. Failure at the copper-to-graphite cold end connection, in some of the earlier tests, was caused by excessive heating due to high electrical contact resistance.

One problem which was not expected was excessive heating of the vessel closure nut and carriage assembly due to induced voltage. The exact amount of induced power was not determined because of the complexity of the ground loop circuits; however, it was sufficient to cause overheating of the electrical insulators and also damage carriage rollers and track. This problem was solved by water-cooling the carriage assembly and installing grounding straps between the carriage and its support structure.

Heater performance tests were conducted in the pressure range of 200 through 600 atmospheres in increments of 100 atmospheres. Nominal gas temperature variation at each operating pressure was from ambient to 2700° Rankine. Originally, as mentioned previously, it was planned to operate at a maximum supply pressure of 700 atmospheres; however, the power supply limited operation to roughly 600 atmospheres. This limitation was the result of a 10,000-ampere current limitation on the power supply, in conjunction with an element resistance which was lower than anticipated. The current limit was based on a required time of approximately four minutes to reach operating power and establish constant pressure and temperature conditions (see Fig. 4). Figures 9 and 10 show measured element resistance and power supply output requirements as a function of measured gas temperature at each pressure level tested. It is possible to increase the operating pressure limit by:

a. addition of more thermal insulation

b. reducing operating time thus permitting higher allowable current

c. increasing element length thus increasing resistance and consequently heat transfer surface

d. improving heat transfer characteristics of the element gas passage configuration

Increasing length or optimizing flow passage configuration would increase pressure drop across the element and possibly additional structural problems. Figure 11 shows the pressure drop characteristics of the element tested. For the tests reported herein, no attempt was made to optimize efficiency. Figure 12 shows the heater efficiency obtained as a function of gas temperature at the various pressure levels. It is felt that the nonuniformity of efficiency variation with pressure level, as shown by the curves, is within the accuracy of the parameters (pressure, temperature, current, voltage and gas properties) used to compute efficiency.

Data of Figures 9, 10, 11 and 12 are based on measured gas temperatures using platinum versus platinum-rhodium thermocouples. Figure 13 shows a comparison of the measured temperatures with those determined by mass flow measurements at a supply pressure of 500 atmospheres. The flow rates were determined from mass flow versus pressure drop calibrations of the flow meter at constant inlet pressures. The mass flows thus determined were used with Figure 2 at the operating pressure to obtain the gas temperature. Temperatures determined by the mass flow method, as shown in Figure 13, are lower than the direct measurements. This lower value was due to leaks in the piping system downstream of the flow meter. A calculation shows that for a fixed operating pressure, a constant leak rate correction would give temperature agreement over the total temperature range.

7. CONCLUSIONS

The heater data for this paper were all obtained from the same element. Total operating time of this element was in excess of one hour and consisted of three separate test runs. Tests of other identical elements showed the same characteristics.

It is felt that this element configuration can be successfully packaged in a three-phase configuration that will satisfy requirements for the Mach 12 capability as specified in Figure 1.

8. REFERENCES

(1) Humphrey, R. L., Little, N. J., Seeley, L. A., "Mollier Diagram for Nitrogen," AEDC TN 60-83, May 1960.

(2) Din, F., Thermodynamic Functions of Gases, Vol. 3, Butterworths, 1961.

(3) Harris, E. L., Carner, J. W., Pasiuk, L., Wint, C. T., "NOL's Mach 17 Nitrogen Wind Tunnel," NOLTR 64-128, Sep 1964.

(4) Shreeve, R. O., Lord, W. T., Boersen, S. J., Bodgonoff, S. M., "A Graphite Heater for a Hypersonic Wind Tunnel Using Nitrogen," Princeton University Report 560, AFOSR 1028, Jun 1961.

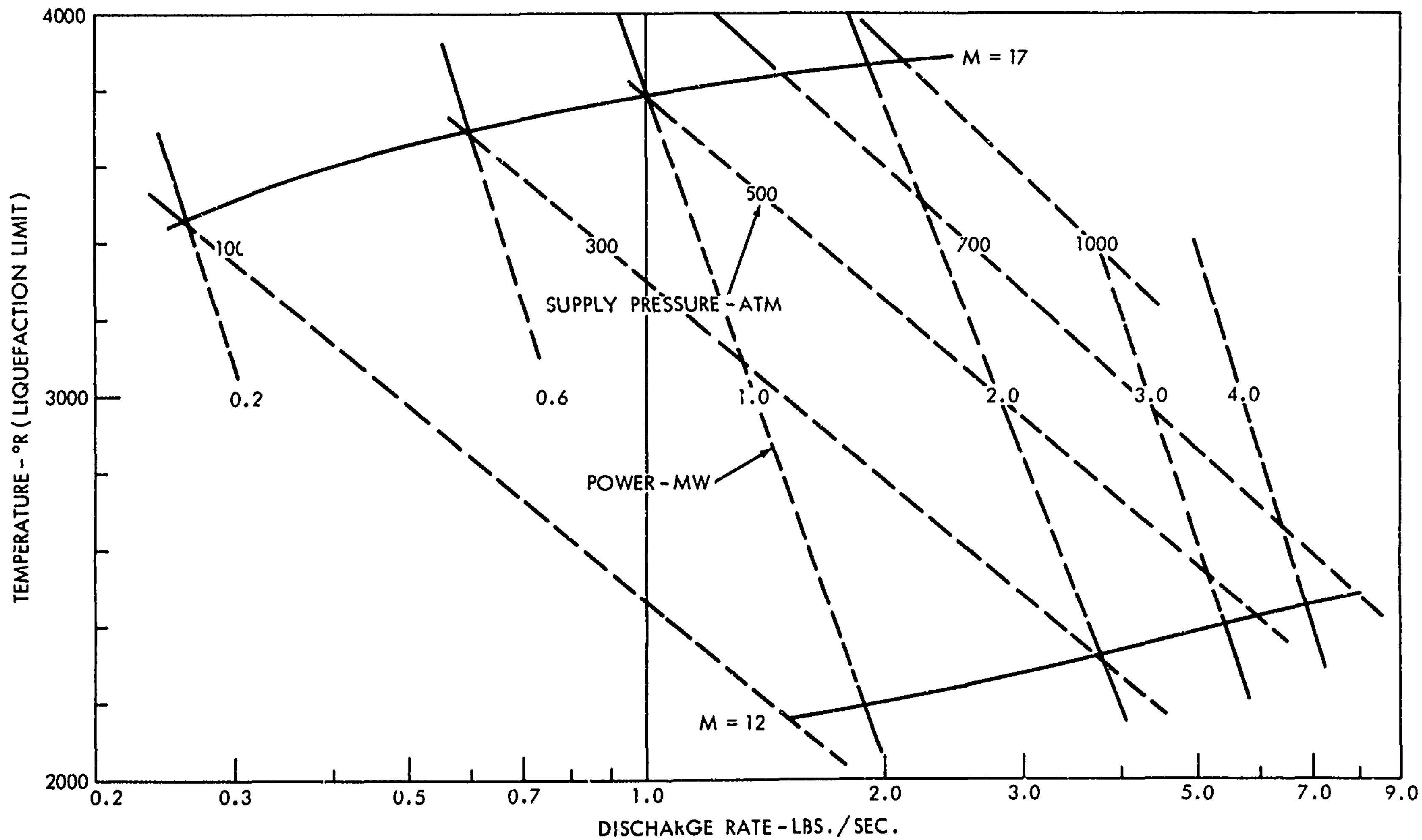

FIG. 1 CONDITIONS REQUIRED FOR LIQUEFACTION FREE FLOW AT M-12 AND M-17

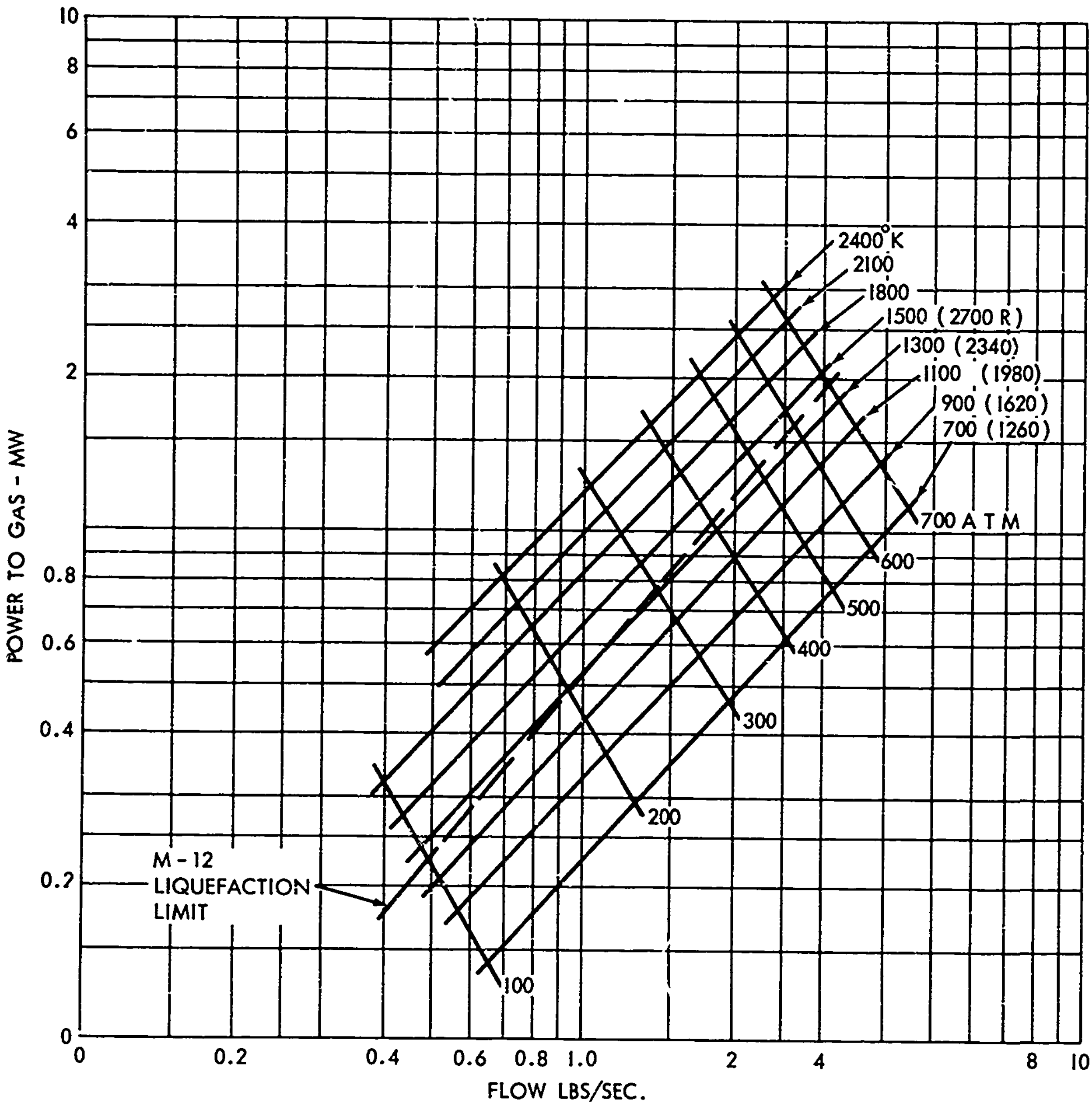

FIG. 2 OPERATING ENVELOPE FOR THE MACH 12 SINGLE PHASE HEATER

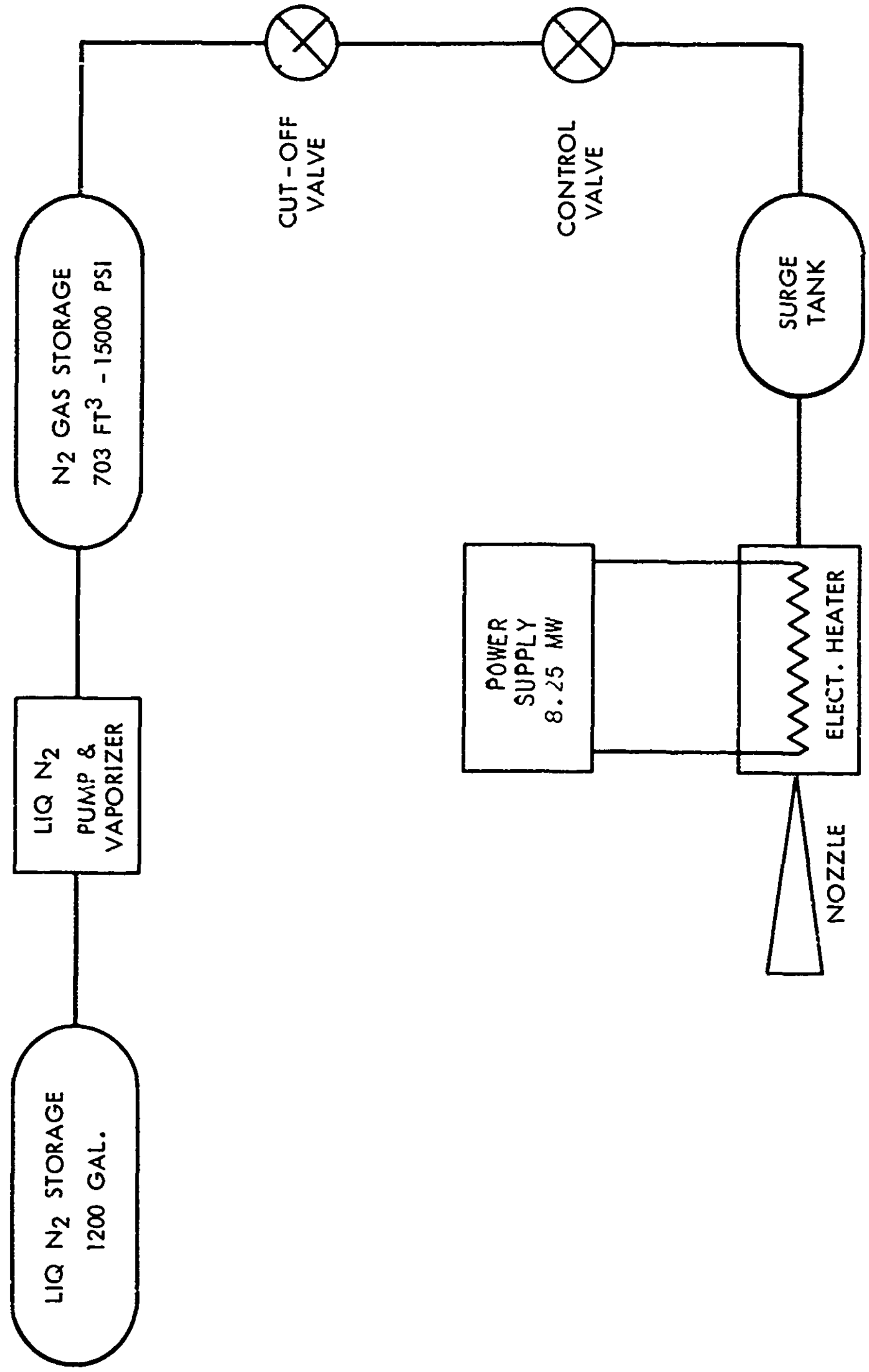

FIG. 3 - LINE DIAGRAM OF EQUIPMENT TEST SETUP

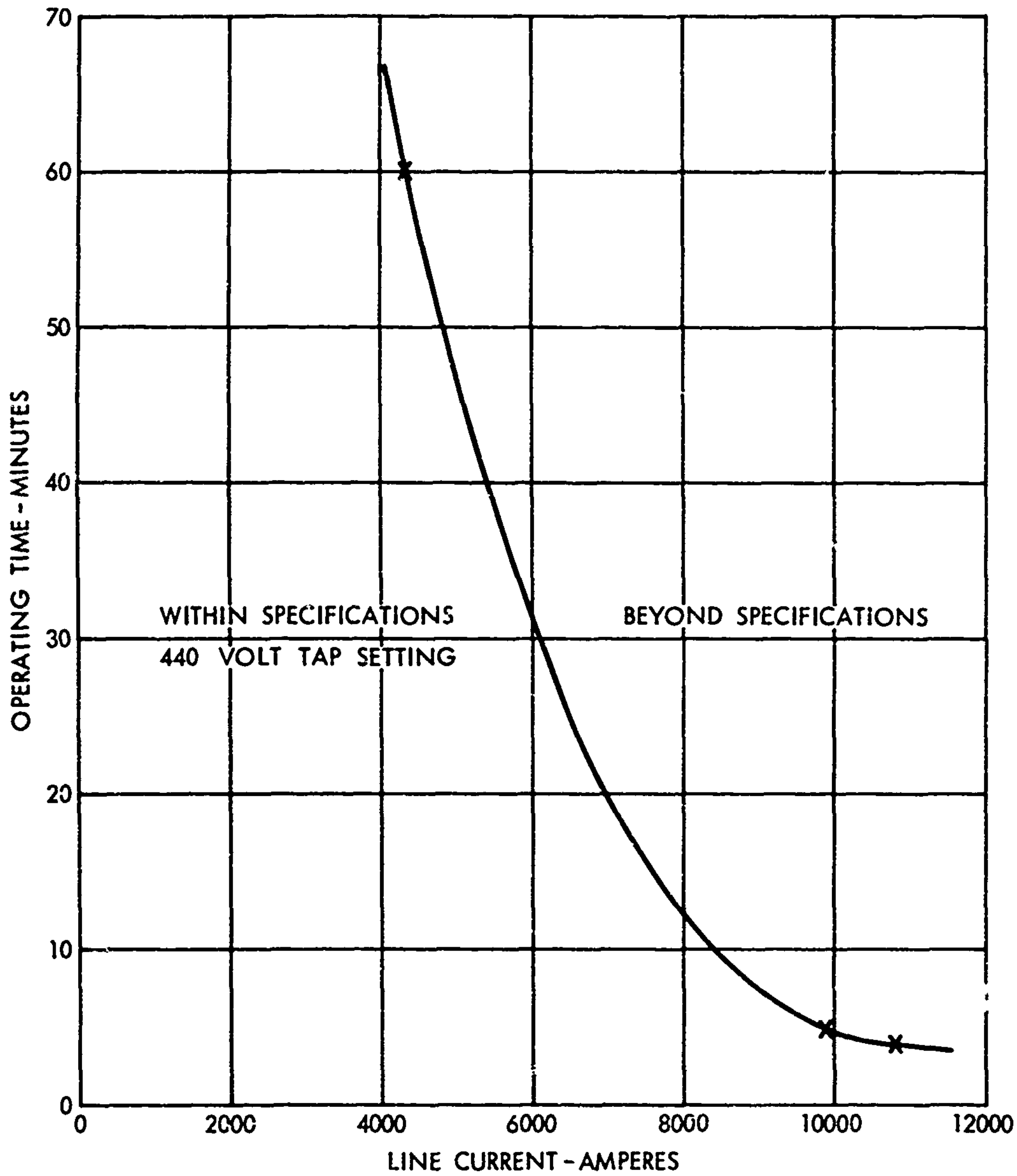

FIG. 4 TIME-CURRENT CHARACTERISTIC OF THE INDUCTROL POWER SUPPLY

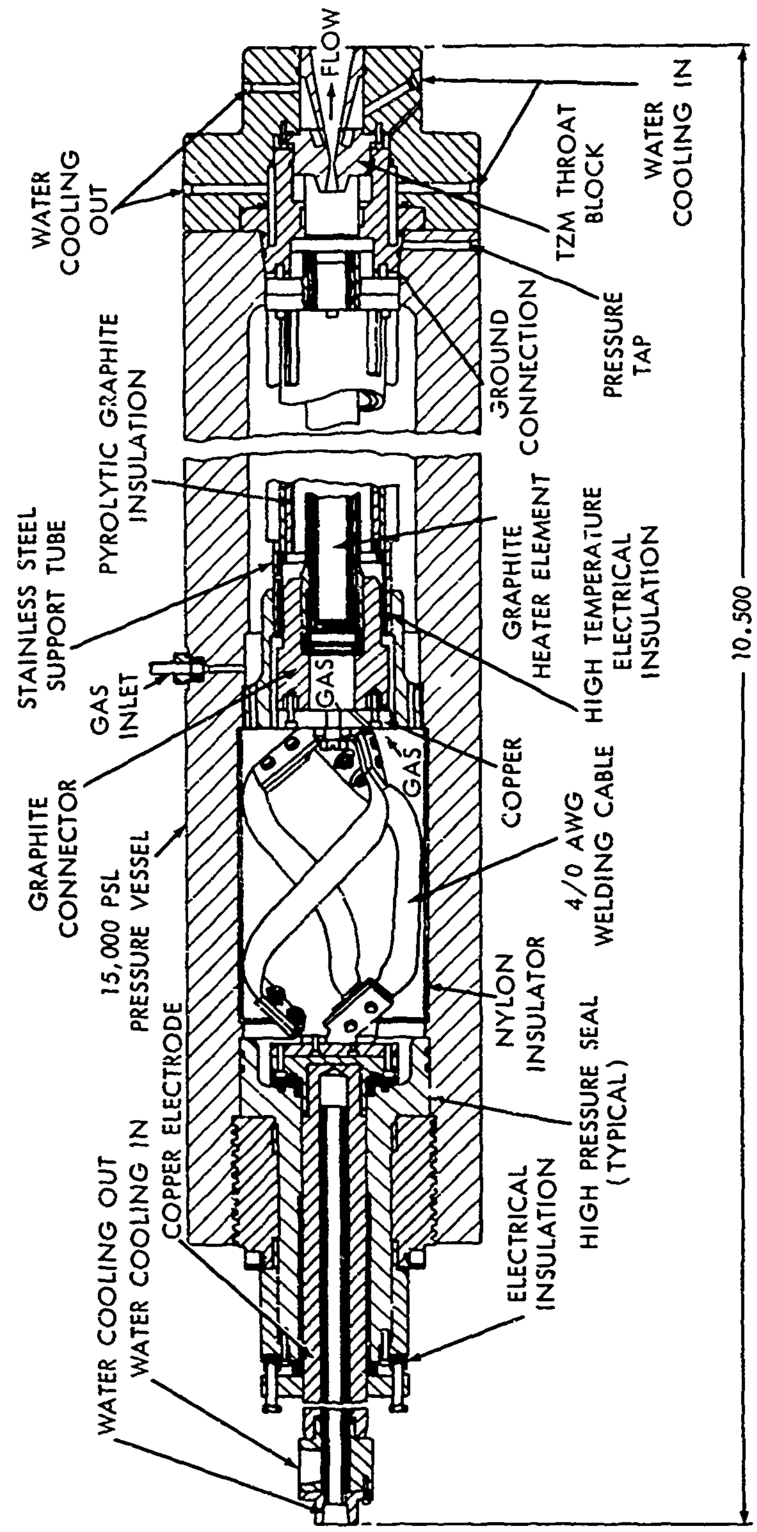

FIG. 5 CROSS SECTION DRAWING OF HEATER ASSEMBLY

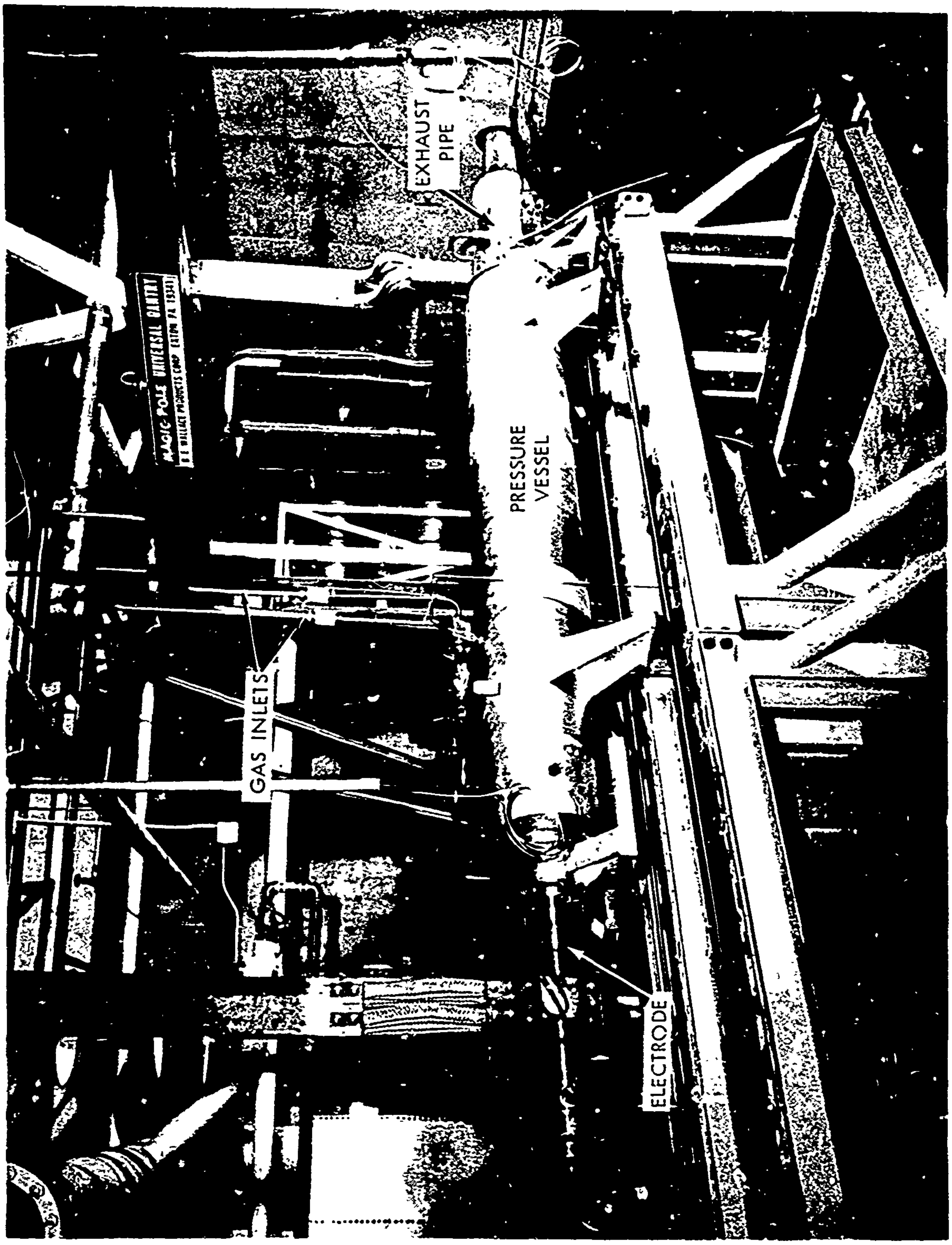

FIG. 6 PHOTOGRAPH OF HEATER TEST SETUP

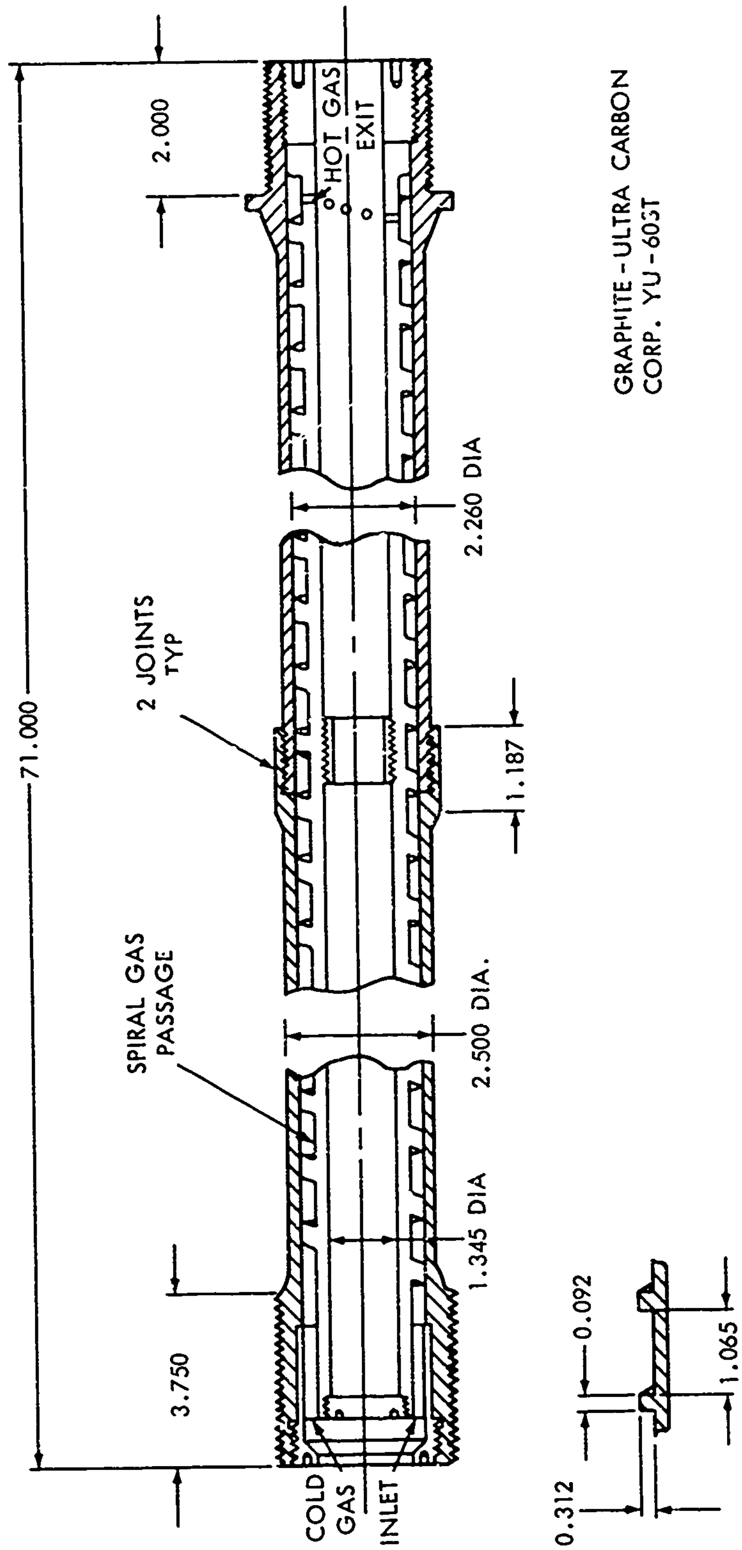

FIG. 7 GRAPHITE HEATER ELEMENT

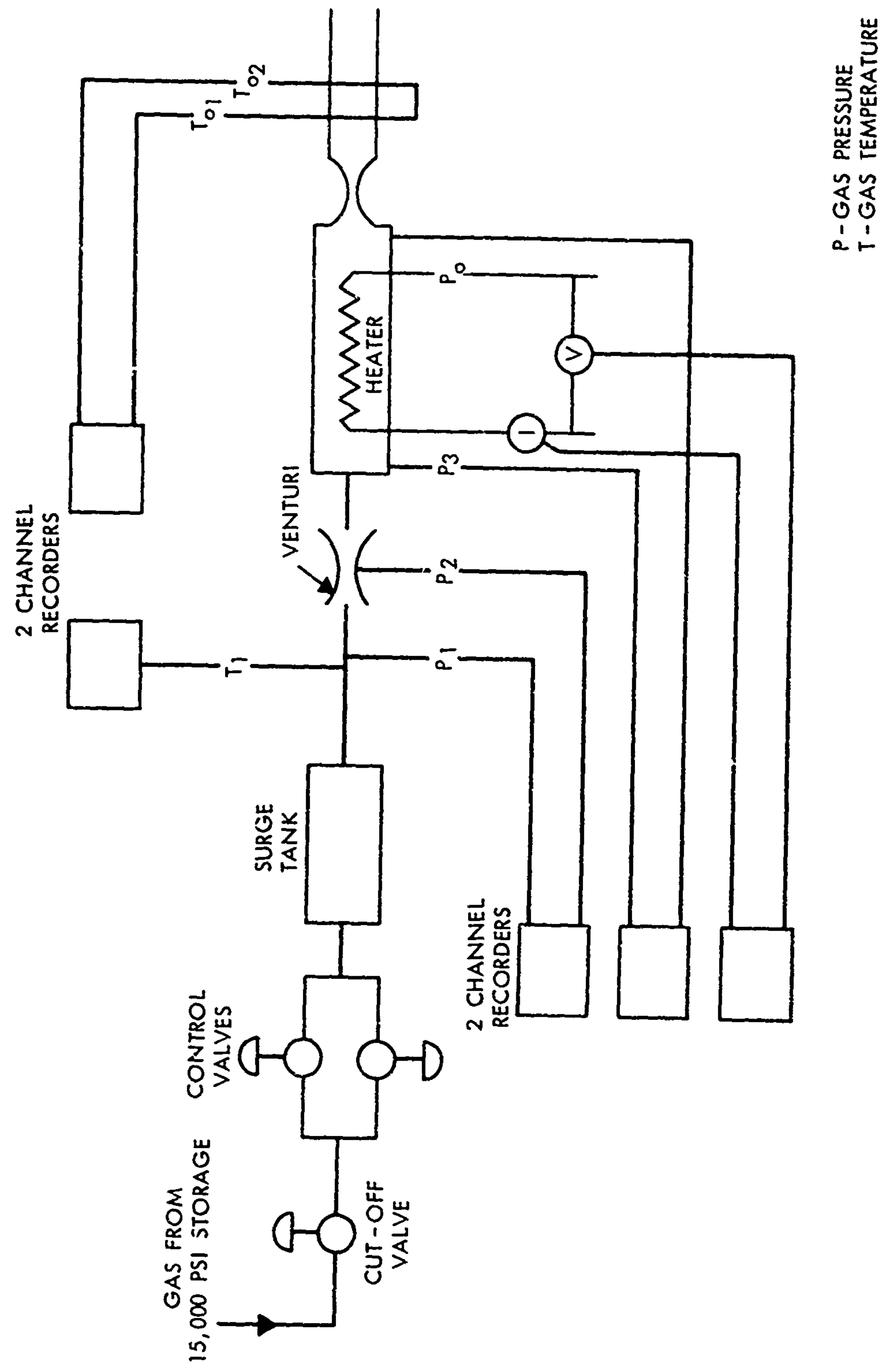

FIG. 8 INSTRUMENTATION SCHEMATIC DRAWING

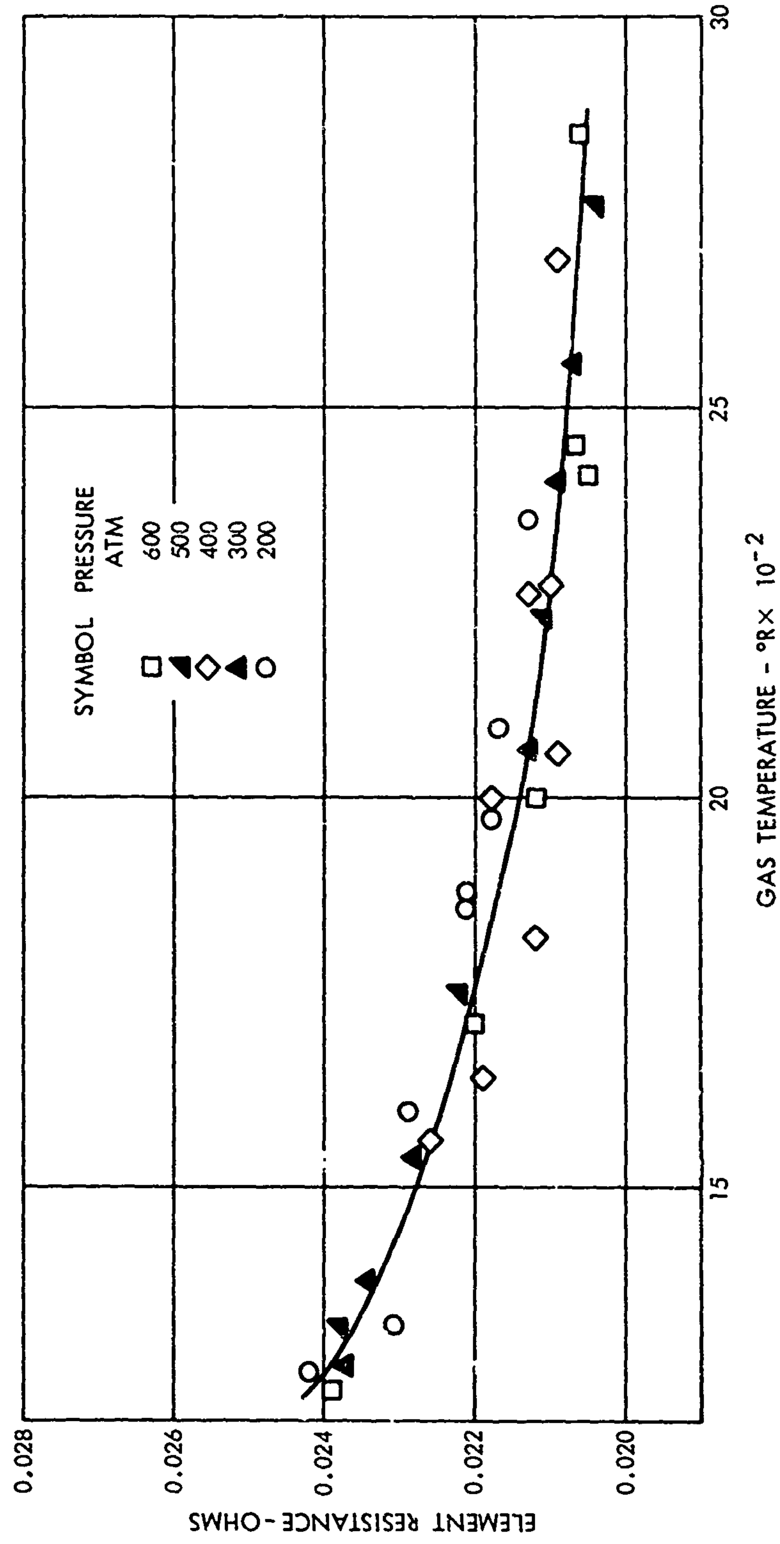

FIG. 9 ELEMENT RESISTANCE VS GAS TEMPERATURE

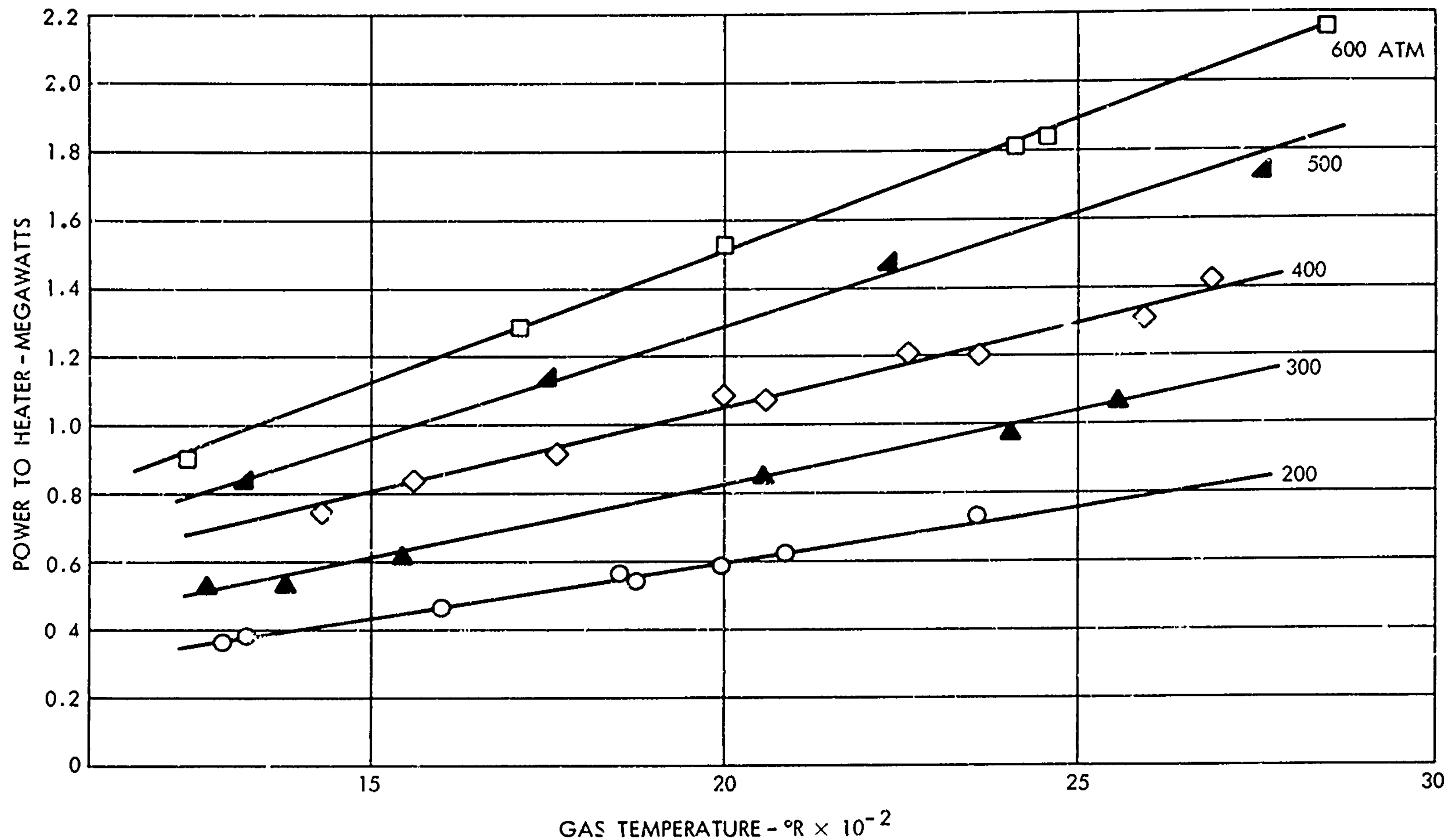

FIG. 10 MEASURED POWER TO HEATER VS GAS TEMPERATURE

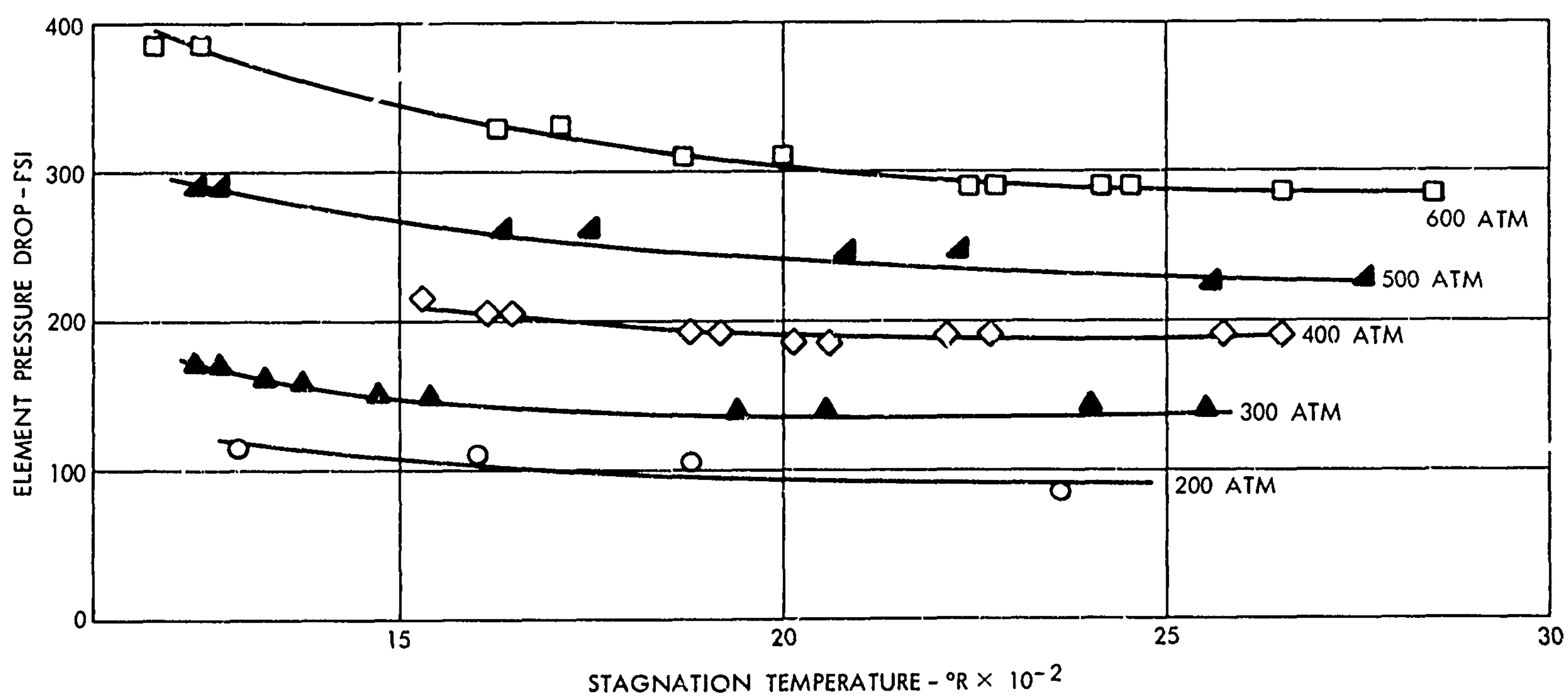

FIG. 11 ELEMENT PRESSURE DROP VS STAGNATION TEMPERATURE

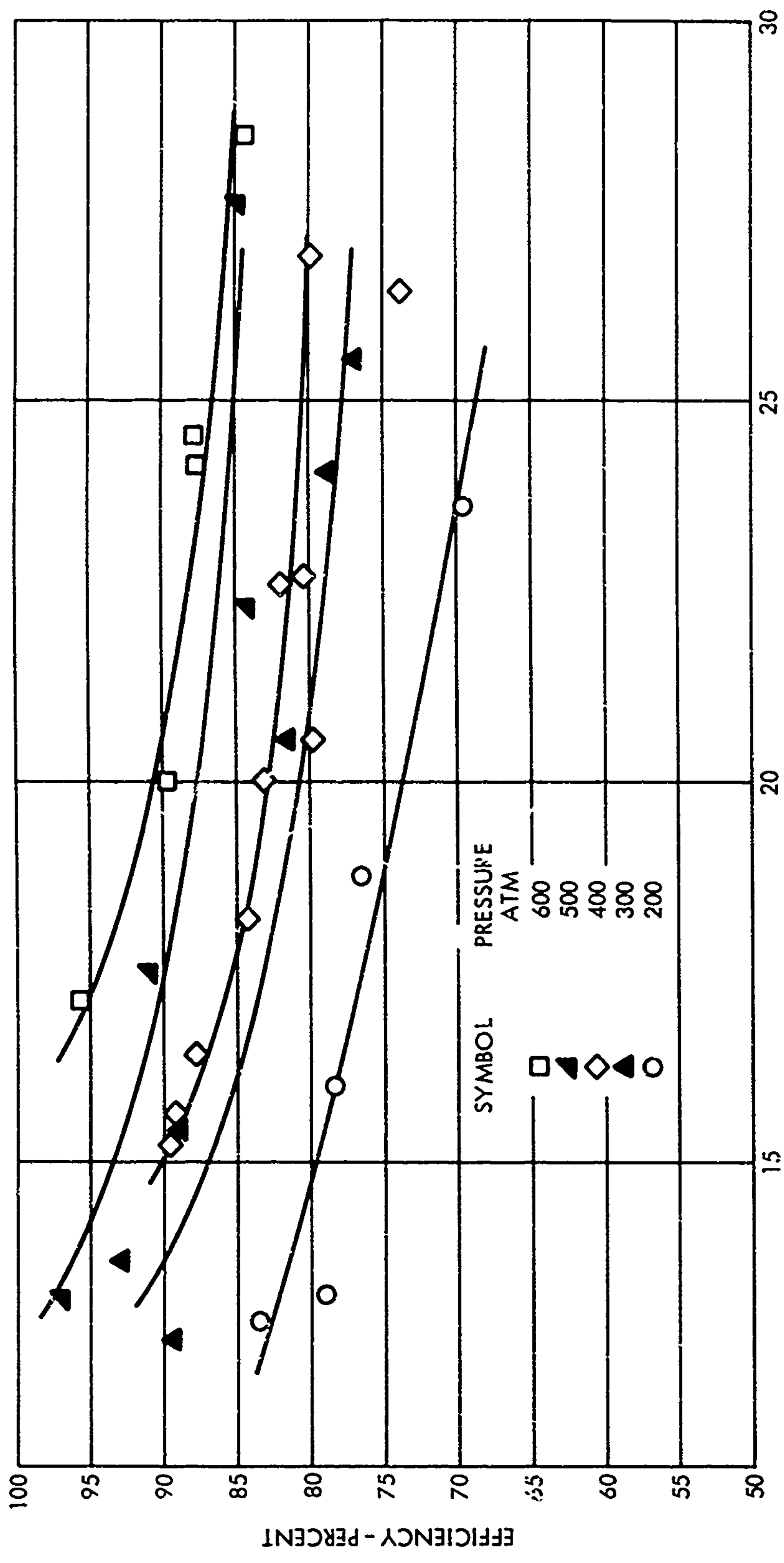

FIG. 12 HEATER FICIENCY

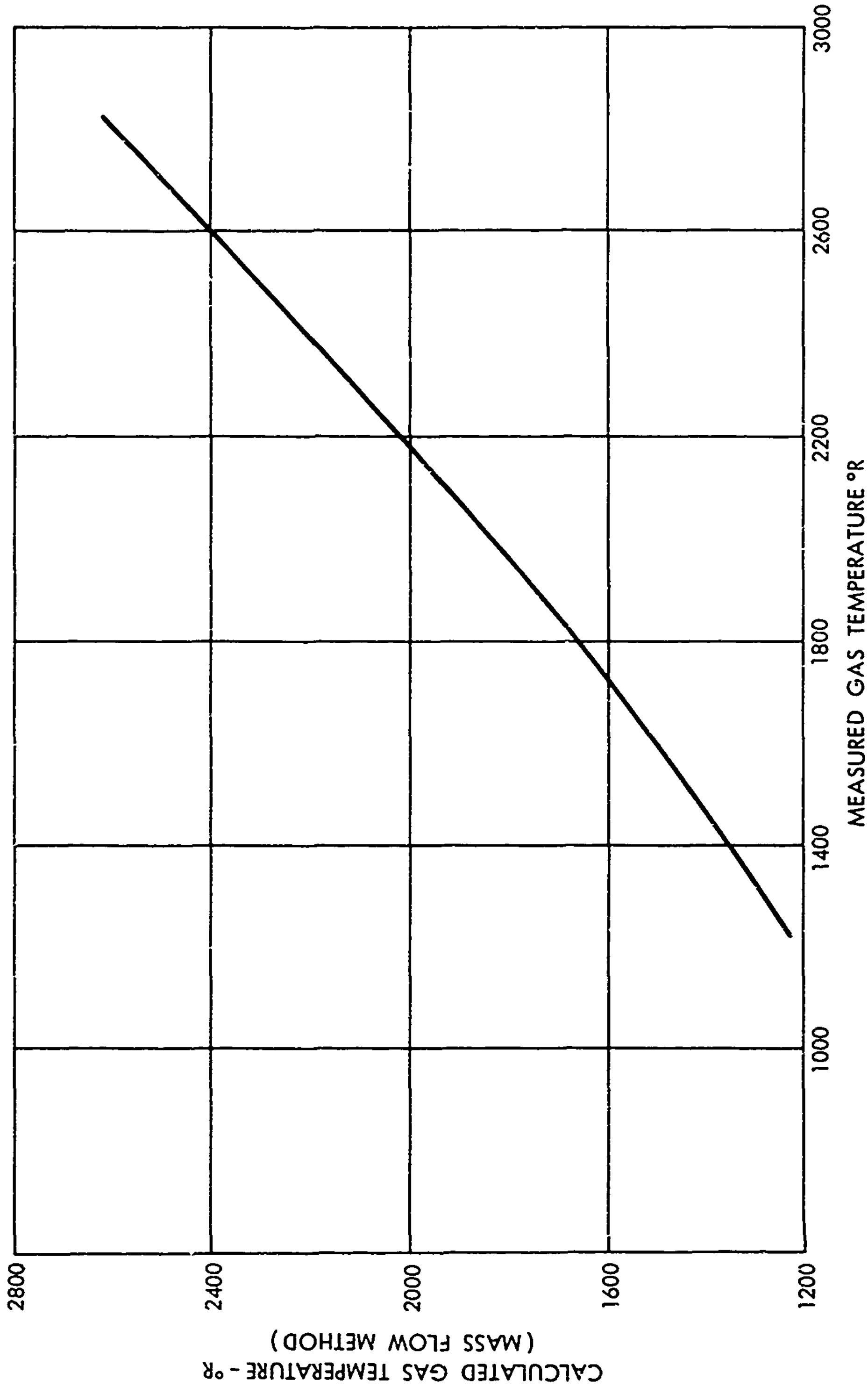

FIG. 13 CALCULATED TEMPERATURE VS MEASURED TEMPERATURE

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 68-109).
A 2.5-MEGAWATT GRAPHITE HEATER FOR NITROGEN GAS, by R. H. Cornett and others. 25 June 1968. 7p. charts. ONM task MAT 03L 000 F008 98 12.

UNCLASSIFIED

This report describes a low-voltage, single-phase graphite heater which will deliver 1.5 pounds of nitrogen gas per second at a pressure of 600 atmospheres and at temperatures up to 2500° Rankine.

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13. ABSTRACT

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